Salt River Project Canal Automation Pilot Project: Simulation Tests

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Abstract: The feasibility of automatically controlling water levels and deliveries on the Salt River Project (SRP) canal system through computer-based algorithms is being investigated. The proposed control system automates and enhances functions already performed by SRP operators, namely feedforward routing of scheduled demand changes, feedback control of downstream water levels, and flow control at check structures. Performance of the control system was tested with unsteady flow simulation. Test scenarios were defined by the operators for a 30 km, four-pool canal reach. The tests considered the effect of imperfect knowledge of check gate head-discharge relationships. The combined feedback-feedforward controller easily kept water level deviations close to the target when dealing with routine, scheduled flow changes. Those same routine changes, when unscheduled, were handled effectively by the feedback controller alone. The combined system had greater difficulty in dealing with large demand changes, especially if unscheduled. Because feedback flow changes are computed independently of feedforward changes, the feedback controller tends to counteract feedforward control actions. The effect is unimportant when dealing with routine flow changes but is more significant when dealing with large changes, especially in cases where the demand change cannot be fully anticipated.

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Introduction

The Salt River Project (SRP) is a public utility that delivers water and electrical power to the Salt River Valley in Central Arizona. The project was originally designed to irrigate 100,000 ha (22,000 acres) of land. Today, over 85% of the area is urbanized and most of the water is delivered to water treatment plants and other municipal users.

Water delivery operations have evolved at SRP in response to changing service demands, water control technologies, and constraints imposed on delivery operations. As part of this evolution, a pilot project was initiated in 1996 to develop and test a canal control algorithm on a portion of SRP's canal system (Gooch 1996). This project is an in-house (SRP) research and development project, with cooperation from the United States Water Conservation Laboratory (USWCL), United States Department of Agriculture, Agricultural Research Service. The objective of this paper is to describe the proposed control system and to present simulated control test results.

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Current SRP Canal Operating Procedures

SRP has a canal system consisting of more than 2,000 km (1,250 mi) of open-channels and pipelines. Water stored in a system of six reservoirs on the Salt and Verde Rivers supplies main canals on the north and south sides of the Salt River (Arizona and South Canal, respectively, as shown in Fig. 1). Both main canals can deliver up to 45 m^3/s (1,600 cfs). SRP also pumps groundwater at various points within the network and delivers water for the Central Arizona Project.

SRP operates as an arranged delivery system and already provides a relatively flexible service. Customers can submit water orders 24 h in advance, and can specify both the flow rate and timing of a new delivery, cutoff, or flow change, subject to constraints dictated by canal capacity and flow travel time from upstream reservoirs. Same-day orders can be serviced if they can be offset by other same-day requests or under emergency conditions (e.g., system shutdowns in anticipation of major storms, unanticipated shutdowns by water treatment plants, damage to the infrastructure, accidents).

The water control strategy consists of maintaining water levels close to a target value upstream from check structures (cross-regulators). Lateral canal and turnout gates located immediately upstream from those check structures are adjusted based on the target water levels and the desired discharge. Most of these offtakes are operated manually but a few are under

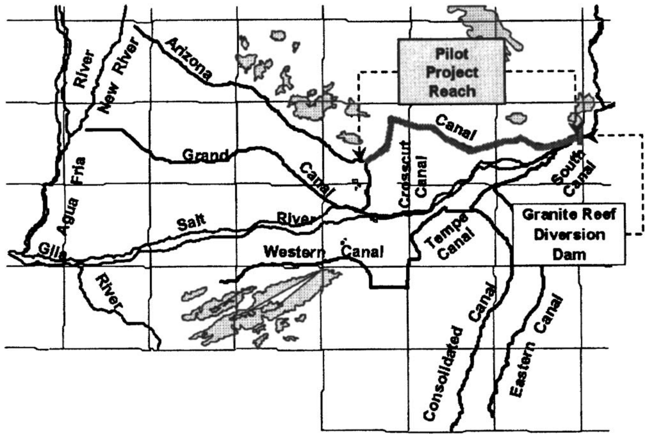

Fig. 1. Layout of SRP's canal system showing the pilot project study reach

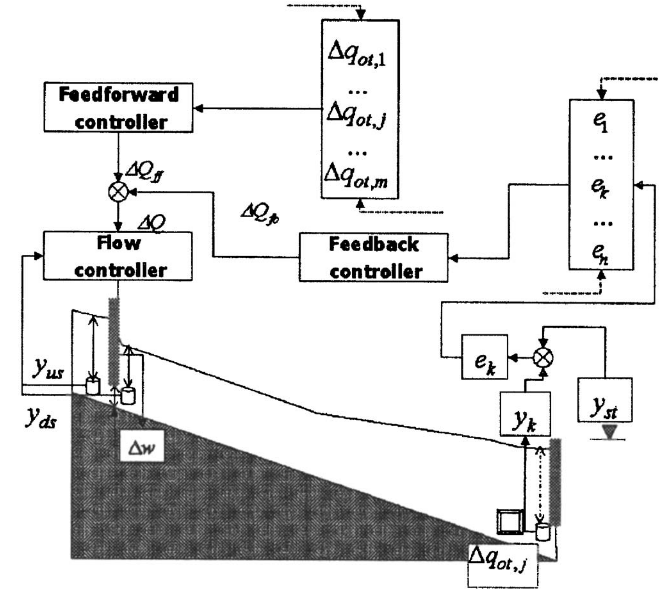

Fig. 2. USWCL canal control scheme shown for one pool

automatic control; in such cases, the gate opening is adjusted based on discharge measured downstream from the offtake, with a broad-crested weir.

For routine conditions, canal operations consist of scheduling known demands (feedforward control) and later making small flow adjustments in response to observed forebay water level fluctuations (feedback control). Routing of known water orders is done daily based on experience (Clemmens et al. 2001). Because of system noise and unquantified perturbations (check gate, offtake gate, and discharge measurement structure calibration errors, and unaccounted for system losses and gains), the schedule can be altered during the day depending on water level trends observed throughout the canal.

A supervisory control and data acquisition (SCADA) system allows main canal operators, known as watermasters, to remotely monitor water levels and operate check gate structures and a few lateral and offtake gates. In order to ensure accurate deliveries and safe canal operation, SRP managers have defined three ranges of water-level deviations to guide canal operations. The SCADA system reports those deviations using color-coded bars. The watermasters' objective is to keep deviations within the range ±7.6 cm (0.25 ft). This dead-band or tolerance range is displayed in green. Deviations that need to be monitored closely and possibly adjusted [between ±7.6 and ±12.2 cm (0.40 ft)] are shown in yellow, while values needing immediate attention and adjustments (>±12.2 cm) are shown in red. The SCADA system also displays the recent water level history for each pool, from which trends (rises and drops) and possible flow imbalances can be discerned. Last, the system also displays levels and discharges at dedicated measurement stations and at cross-regulators. Discharge values from measurement stations are generally reliable but check-gate values are not, especially if the gate is submerged. All of this information is used by watermasters to determine feedback control actions, including changes to the feedforward schedule. Because of the large number of pools involved, the uncertainty of flow rate measurement, and the fact that flow corrections changes are determined based solely on experience, watermasters take a wait-and-see approach after making any change and try to minimize the number of flow adjustments.

Proposed USWCL Control System

System Components

The proposed control system consists of three separate controllers working in a master-slave configuration (Fig. 2). In the diagram, which shows a single pool in a multiple-pool canal, solid connectors represent inputs from the depicted pool to the controllers and outputs from the controllers to that pool's upstream check structure. The dotted unconnected arrows represent inputs from other pools and outputs to other check structures. The feedforward controller uses preestablished canal hydraulic relationships to determine a schedule of upstream flow changes, ΔQ_{ff}, needed to deliver known offtake flow changes Δq_{ot}. A schedule is computed for each check structure based on the demand changes from all pools, which are represented by the top middle box in the diagram. The feedback controller responds to system noise and unanticipated perturbations. It uses the forebay water levels y to compute deviations, e, with respect to the setpoint, y_{stp}. The deviations are then used to determine flow rate feedback control signals ΔQ_{fb}. ΔQ_{ff} and ΔQ_{fb} are summed by the slave flow controller to determine a net change in flow setpoint ΔQ for each check structure. The flow controller periodically adjusts the opening of each check gate, Δw, to deliver the requested ΔQ, based on water levels upstream and downstream from the gate, y_{us} and y_{ds} in Fig. 2. With this master-slave configuration, control actions are computed independently of gate hydraulics.

Feedback Control Algorithm

Clemmens and Schuurmans (2004) proposed a class of multivariable feedback controllers for open-channels. They have the following features:

- Their objective is to maintain constant water levels at the downstream end of pools.
- They are centrally operated, that is, monitoring and determining control actions is done from a remote site.
- The control law is derived using discrete state-variable control principles. In such an approach, physical system dynamics

are represented by a system of linear ordinary differential equations of the form

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}\mathbf{u}(k) \tag{1}$$

$$\mathbf{e}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{D}\mathbf{u}(k) \tag{2}$$

These equations approximately represent the relationship between inputs and outputs measured at discrete times. Variables are $\mathbf{x}(k)$=vector of system states at discrete time k; $\mathbf{u}(k)$=vector of control actions; $\mathbf{e}(k)$=vector of outputs; and $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, and $\mathbf{D}$=matrices that depend on the system's physical properties and are known as state-transition matrices. The dimensions of $\mathbf{u}$ depend on the number of controlled gates; of $\mathbf{e}$ on the number of measured outputs; of $\mathbf{x}$ on measured outputs and additional states that need to be incorporated in the control problem formulation; and of matrices $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, and $\mathbf{D}$ on the dimensions of the $\mathbf{x}$, $\mathbf{u}$, and $\mathbf{e}$ vectors. The feedback law's mathematical expression is

$$\mathbf{u}(k) = -\mathbf{K}\mathbf{x}(k) \tag{3}$$

in which $\mathbf{K}$=controller gain matrix; and $\mathbf{u}$, $\mathbf{x}$, and k are as defined above. Controller design involves finding $\mathbf{K}$ subject to constraints imposed by the system dynamics, Eqs. (1) and (2).

- In previous studies, state-variable representations of the open-channel flow system were developed by discretizing and linearizing the governing Saint-Venant equations [e.g., Balogun et al. 1988). Clemmens and Schuurmans' (2004)] approach is much simpler, as it uses a lumped-parameter pool dynamics model, named integrator-delay (ID) model (Schuurmans et al. 1995). The ID model relates pool downstream water level variation as a function of time to upstream inflow changes; the response depends on the pool's backwater characteristics. The model was developed assuming ideal outflow control but can be used to characterize the response of pools with gravity offtakes, in which discharge varies with water levels. Like the state-variable relationships developed by discretizing the unsteady-flow equations, integrator-delay parameters are characterized for a specific, representative set of flow conditions. Those parameters are contained in the state-transition matrices $\mathbf{A}$ and $\mathbf{B}$.
- State-variable equations are obtained by expressing the integrator-delay model relationships in difference form. The controller gain matrix in Eq. (3) can then be configured to provide proportional and integral control action, and also to account for the delayed effect of past control actions. The resulting state vector $\mathbf{x}$ includes current water level errors, changes in water level errors, and previous control actions. Only the forebay depth needs to be measured in each pool (see Fig. 2). The resulting control action vector $\mathbf{u}$ consists of flow rate changes (which then have to be converted to gate setting changes by a flow controller, as discussed in a later section).
- Different controllers can be formulated using the same matrix structure and solved for $\mathbf{K}$ using optimal control techniques. Controllers differ depending on which forebay depths are allowed to influence flow changes at particular check structures. The most complex configuration is a fully centralized optimal controller, in which all measured depths affect all control actions simultaneously. This controller can be classified as a linear quadratic regulator (LQR)-type controller. The simplest configuration consists of the case in which a check flow change depends only on its downstream forebay, which is equivalent to a set of independent (but centrally tuned) proportional-integral (PI) controllers.

Clemmens and Schuurmans (2004) examined different controller configurations and potential performance, using as an example the test canal discussed below. For this paper, most tests were run with one of their recommended controllers, a PI controller that also passes information from one pool water level to all gates upstream and one additional gate downstream (which they named PI_{-1}^{+} controller). Delays due to wave travel time are not accounted for by this controller. Some tests were also run with the fully centralized PI controller mentioned in the previous paragraph, which accounts for delays and past control actions (PIL_{-}^{+}). Both controllers were designed for a 30 min feedback control interval (the interval between successive control actions) and tuned assuming discharge in each pool was 60% of capacity (approximately the initial flow conditions considered in Scenario 1). Additional details on the controllers' mathematical formulation and a discussion of procedures for selecting a feedback control interval and for tuning these controllers are provided in Clemmens and Schuurmans (2004).

Feedforward Control Algorithm Functions

In open-channels, feedforward control is the process by which control actions are carried out prior to an expected change in downstream withdrawals. Such precompensation is needed because of the long time that is typically needed for flow changes to travel from the upstream-most control point to the site with the demand change. The feedforward control method applied herein is based on volume-compensation principles (Bautista and Clemmens 2005). This method computes a schedule of check flow changes needed to meet the new demands from pool storage changes and wave travel time estimates. The procedure assumes stepwise demand changes.

Changes in pool storage ΔV are computed assuming initial and final steady states in between demand changes, even if such conditions cannot be reached in practice. For a single pool, the wave travel time or delay $\Delta\tau$ is calculated as the ratio of ΔV and Δq_{ot}. This volume-based delay has been tested with single-pool canals under a wide range of subcritical flow conditions and shown to produce satisfactory water level control (Bautista et al. 2003). Multiple-pool, multiple-demand problems can be solved as a series of linearly additive, single-pool, single-demand problems (Bautista and Clemmens 2005).

Flow Control System Functions

The flow setpoint at every check structure needs to be modified in accordance with the schedule of computed feedback and feedforward flow changes. The new flow setpoints then need to be translated into actual gate openings. Finally, since water levels upstream and downstream from check structures vary during the transient, check gates need to be adjusted periodically to match the actual discharge with the target. The flow controller performs these functions. Independent flow control calculations remove gate nonlinearities from the feedforward and feedback control design calculations. The flow controller applies feedback changes (i.e., modifies the flow setpoint and adjusts the gates to deliver the new flow rate) at every feedback control interval ΔT_{fb}. Additional gate adjustments are made in between feedback intervals to match the flow setpoint at every flow control interval ΔT_Q. Hence the flow control interval is given by $\Delta T_Q = \Delta T_{fb}/n$, where n=integer greater than or equal to 1. The feedforward calculations are independent of ΔT_{fb} and ΔT_Q. However, the schedule can be adjusted so that changes are applied only at discrete time

Table 1. Upper Arizona Canal Properties. Manning n is 0.018 for All Pools

Pool number	Forebay name	Forebay number	Length (km)	Bottom width (m)	Side slope	Bottom slope	Capacity (m^3/s)
0	Granite Reef	1-00-0	—	—	—	—	45
1	Evergreen	1-00-6	12.7	18	1.4	0.00047	45
2	Indian Bend	1-01-9	10.1	20	1.4	0.00035	45
3	Scottsdale Rd.	1-03-0	4.1	20	1.3	0.00022	45
4a	68th St.	1-03-4	1.9	19	1.4	0.00020	45
4b	Arizona Falls	1-05-0	1.6	19	1.4	0.00020	—

intervals. Therefore the flow controller can be configured to apply the feedforward flow changes either at a ΔT_Q or ΔT_{fb} interval. In principle, the flow controller functions do not need to be centralized and can be assigned to programmable remote terminal units.

SRP gate discharges are calculated from the measured heads and their head-discharge relationship. Because these relationships are uncertain, flow rate changes need to be made incrementally. This means that the flow control action is a change in flow rate. For example, if the controller reports a current discharge of 10 discharge units and the requested change is one unit, the controller computes the gate opening increment that will deliver that extra discharge unit, or close to that value. Knowing the actual initial discharge value is irrelevant as long as future closed-loop control actions reduce the actual flow errors and as long as the turnout flow rates are properly set (i.e., each turnout gate is set to provide the demanded flow rate, when the canal water level is at its setpoint level).

Control System Testing

Test Canal

The Upper Arizona Canal, a 30.6 km canal reach, was chosen as the site for testing the control algorithms. The reach consists of four pools, with the last one sometimes operated as two separate pools. The latter condition was not considered here. Average physical properties of the Upper Arizona Canal are summarized in Table 1. The first two pools are relatively long, somewhat steep, and have relatively little backwater from the downstream check structure. Pools 3 and 4 are shorter and entirely under backwater.

Details of the check gate structures and a summary of diversion structure capacities are given in Table 2. The relationships employed by SRP to compute discharge as a function of water levels and gate opening are discussed in Clemmens et al. (1997). These relationships are considered to yield reasonable field-predicted discharges under free flow conditions, with errors within ±8%, but are considered far less reliable under submerged flow conditions (SRP 1996; Clemmens et al. 2001). The four major offtakes in the Upper Arizona Canal are the SRPMIC Lateral (4.2 m^3/s), the SRPMIC Booster Pump (2.5 m^3/s), the Grand Canal (17.7 m^3/s), and the Lower Arizona Canal (31.8 m^3/s) (the Lower Arizona and Grand Canals are actually main canals but they are considered offtakes for purposes of this analysis). The first two offtakes are located in the uppermost pool and the other two in the last pool. The other pools service a few small offtakes and secondary canals. Gates for the larger offtakes are operated from the supervisory control center, while the smaller ones are typically operated locally. For this study, only SRPMIC Lateral, Grand Canal, and Lower Arizona were treated as gravity offtakes (i.e., discharge allowed to vary with water level) while other offtakes were treated as idealized lateral discharge structures.

Simulation with Mike-11

The Danish Hydraulic Institute (DHI) developed a *Mike-11* (version 3.2, DHI 1992) model of SRP's Arizona Canal (Rungo 1995). Tests were conducted on the Upper Arizona Canal to verify the ability of the model to simulate transients (Clemmens et al. 1997). Model-computed water levels matched actual water levels better in some pools than in others. However, water level trends (i.e., the timing and magnitude of level changes) compared favorably in all pools. Hence differences can be explained by gate calibration inaccuracies. Tests were also conducted to verify the accuracy of the numerical solution. Based on these tests, a 1 min time step was selected for all simulations.

The canal control system was programmed into the unsteady flow model *Mike-11* through a user-modifiable dynamic-link library (DLL) especially developed for this study by DHI. Subroutines were developed within the User-DLL to:

- Poll forebay water level data, compute feedback control actions from these data, and submit these changes to the flow controller at each feedback control interval;
- Input the externally computed feedforward schedule for each check structure, determine when in the simulation these changes need to be implemented, and submit these changes to the flow controller; and
- Perform flow control actions at the flow control interval (and at feedforward schedule times), taking into account water levels upstream and downstream from the gate.

Calls to the User-DLL are made through programmable control structures. A programmable structure can represent a check gate or an offtake. A call is made at simulation start-up to identify the programmable structures and collect controller data and the externally computed feedforward schedule. Additional calls are made at subsequent computational time steps, first to determine if a feedforward change is needed or if the calculation is at a

Table 2. Upper Arizona Canal Check Structure Properties

Check ID	Location (km)	Number of gates	Gate flow regime	Combined offtake capacities (m^3/s)
1-00-0	0.0	3	Free	
1-00.6	12.7	5	Free (usually)	6.7
1-01.9	22.8	3	Free	0.7
1-03.0	27.0	3	Submerged to free	1.1
1-05.0	30.6	5	Free	49.8

Table 3. Scenario 1 Initial Check and Offtake Flows, Target Water Levels, and Demand Changes

Forebay and check ID	Initial check flows (m^3/s)	Forebay depth (m)	Major offtakes	Major offtake flows (m^3/s)	Demand change (m^3/s)	Time of change	Final check flow (m^3/s)
1-00-0	30.87						31.44
1-00-6	26.39	2.29	SRPMIC	4.25			26.96
1-01-9	26.28	1.77					26.85
1-03-0	26.22	1.83					26.79
1-05-0	14.81	1.83	2-00-0	11.33	+0.57	6:30 a.m.	14.81
			1-05-0	14.81			

feedback or flow control time step, and if so, then to carry out the necessary control actions. Details of this User-DLL are given in Clemmens et al. (2001) and Clemmens et al. (2005).

Test Scenarios

SRP watermasters developed a series of scenarios to test the control algorithms, three of which were selected for this paper. Initial conditions and demand changes for each scenario are summarized in Table 3. Scenario 1 consists of a small demand change under high initial flow conditions, Scenario 2 of multiple small changes for the same high initial flow, and Scenario 3 a large demand change under initial medium flow. The first two scenarios are representative of typical operations, in which SRP watermasters aggregate demands from the Northside's lower reaches, leaving just a few changes to deal with at Arizona Falls check structure (1-05-0) and the head of the Grand Canal (2-00-0). Scenario 3 is atypical and would occur in the case of an emergency (e.g., a water treatment plant shutdown). A 24-h operational period was assumed for these tests. All of these scenarios assume the offtake with the demand change adjusted once, that is, no additional adjustments are made during the course of the test in response to varying water levels.

The volume-compensation feedforward controller has been examined separately and shown to produce adequate water level control in simulation. The objective here is to analyze the feedback controller alone and in combination with the feedforward controller. Feedback control alone was examined with Scenarios 1 and 3. Combined (feedforward plus feedback) control was applied to all scenarios.

Scenarios 1 and 2 were examined with full precompensation of the demand change (i.e., the demand change was known early enough to compute and apply the volume-compensating feedforward schedule). By definition an emergency change, such as the one considered in Scenario 3, is not known beforehand and cannot be precompensated. Feedforward control actions can still be applied, but at earliest at the same time as the emergency offtake change. In the following discussion, this control strategy will be referred to as nonanticipatory feedforward control. Thus Scenario 3 was examined with and without anticipation of the demand change.

Feedback control actions were determined at every feedback control interval (ΔT_{fb}=30 min), starting from steady-state conditions, using one of the two previously discussed controllers, PI^{+}_{-1} or PIL^{+}_{-}. Check structure flow control was applied in all tests. The effect of the flow control interval ΔT_Q was tested, in the range of 5–30 min. Because performance differences were minimal, results presented here are based on a 30 min interval. As was indicated earlier, the flow controller can be configured to apply the feedforward changes at the scheduled time or at a feedback/flow control interval. For these tests, the first option was used. However, since unsteady flow calculations were performed using a 1 min time step, feedforward changes were actually applied to the nearest minute.

Tests were conducted first with identical head-discharge relationships in *Mike-11* and in the flow controller and then with different relationships to evaluate the effect of imperfect gate calibration. In such cases, the flow controller relationships systematically underpredicted the discharge values by 10% relative to the value calculated by the simulator at the Evergreen forebay (1-00.6); at the Indian Bend (1-1.9) and Scottsdale Road (1-3.0) gates, the flow controller relationship overpredicted discharge by 10%. While the Arizona Falls (1-05.0) check was treated as an offtake for this test, a +10% flow error was also imposed at this location.

Results

Scenario 1

In this scenario, discharge through Structure 2-00-0 increased by 0.57 m^3/s (20 cfs) at 6:30 a.m. (Table 3). The initial simulation was conducted with feedback control only (i.e., the demand was treated as an unscheduled perturbation) using the PI^{+}_{-1} controller and a 30 min flow control interval. No gate calibration errors were imposed on this test to allow us to better understand fundamental controller features. Fig. 3 presents the resulting forebay water level deviations with respect to their respective

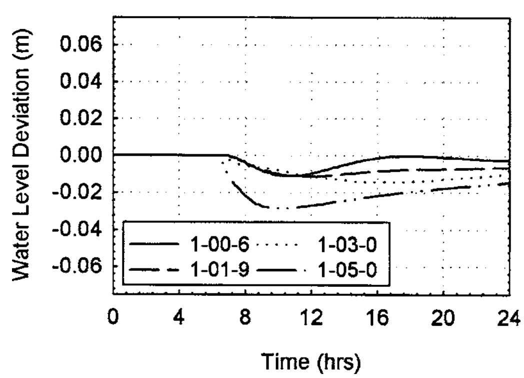

Fig. 3. Water level deviations for Scenario 1: feedback control only (PI^{+}_{-1}), 30 min flow control interval, perfect gate calibration

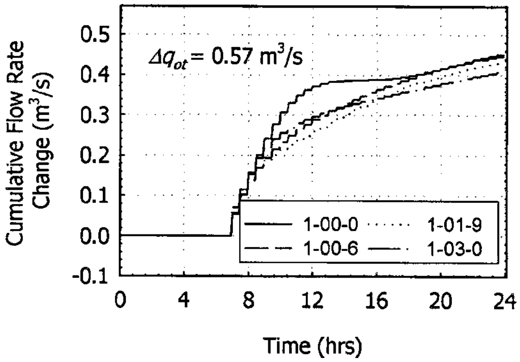

Fig. 4. Cumulative check flow changes for Scenario 1: feedback control only (PI^{+}_{-1}), 30 min flow control interval, perfect gate calibration

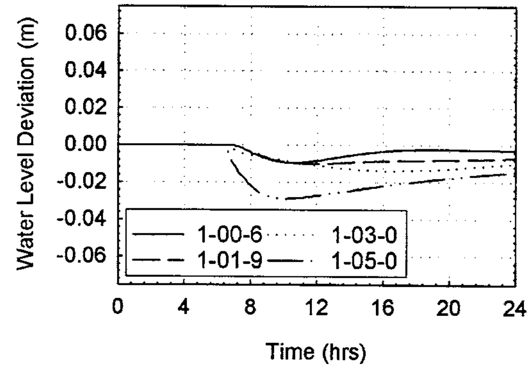

Fig. 5. Water level and flow variations for Scenario 1: feedback control only (PIL^{+}_{-} controller), 30 min flow control interval, perfect gate calibration

setpoints as a function of time. Note that deviations are well within SRP's dead-band or "green zone" [±7.6 cm (0.25 ft)] and, therefore, that performance under the test conditions would meet SRP's operational objectives. The water level in Forebay 1-05-0 began dropping immediately after the offtake change, and reached 3 cm (1.2 in.) 3 h after the change. The water level in Forebay 1-03-0 also dropped shortly after the offtake change, in response to a lower water level downstream from the 1-03-0 check gates (flow through the 1-03-0 gates is submerged). In contrast, check Structures 1-00-6 and 1-01-9 flow free and, therefore, water levels in their corresponding forebays were not affected until 30 min after the offtake change, as a result of feedback-controller requested flow changes. Eventually, water levels began to recover in all pools and the magnitude of deviations decreased to at most 1.5 cm (0.6 in.) by the end of the day. Additional calculations have shown that it takes 22 more h for water levels deviations to decrease by another 1 cm.

The cumulative flow changes requested by the controller [$\Sigma\Delta Q_{fb}(t)$] are shown in Fig. 4. In response to the initial drawdown in Forebay 1-05-0, the controller requested a 0.07 m^3/s (2.5 cfs) flow increase (13% of the unscheduled demand change) at the next two upstream check structures, and slightly smaller changes further upstream. Subsequent flow changes were progressively smaller so that by the end of the test, the net flow change through any of the check structures was only between 72 and 80% of the demand change.

Overall, these results show that the feedback controller alone can reject small flow perturbations. The controller responded to the small initial water level drawdown and continued to request flow increments as water levels continued to drop. However, the computed flow changes became progressively smaller as the drawdown rate decreased. The reduction in drawdown rate is explained by reductions in gravity-dependent offtake discharge with decreasing water levels. This interaction between water levels and offtake discharges also helps explain why levels recover even though the cumulative inflow increment does not match the unscheduled demand change.

Recall that the integrator-delay model, which provides the foundation for the feedback controller design, assumes idealized flow control. These results also show that the ID model represents adequately the response of pools with gravity-dependent outflows. Hence, insofar as the controller is concerned, gravity-dependent flow variations are simply additional perturbations that need to be rejected. This points out the possibility of improving the controller's response by accounting for the effect of lower water levels on target offtake discharges. Our controller design method presently does not provide a mechanism for incorporating such known disturbances.

A test similar to the one presented above was conducted using the fully centralized PIL^{+}_{-} controller, which transmits control signals to all gates in both directions and tries to account for time delays (in contrast, the PI^{+}_{-1} controller ignores past control actions and transmits control signals to all upstream gates and to the next downstream gate). Water level deviations computed with the PIL^{+}_{-} controller (Fig. 5) were similar to those obtained with the PI^{+}_{-1} controller (Fig. 3). For this canal reach, the PIL^{+}_{-} controller gain matrix elements associated with signals transmitted more than 1 pool in the downstream direction are small in comparison with other matrix elements and, thus, their impact on the computed control actions is small (see Table 1 in Clemmens and Schuurmans 2004). The PI^{+}_{-1} controller simply sets those terms equal to zero.

Combined feedback and feedforward control was applied to this scenario. The simulation was conducted again using the PI^{+}_{-1} controller and without gate errors. As expected, the combined system was more effective in maintaining water levels close to their targets (Fig. 6) than when using feedback control alone

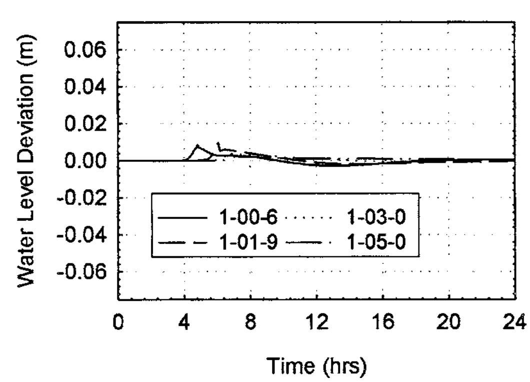

Fig. 6. Water level deviations for Scenario 1: feedback (PI^{+}_{-1}) and feedforward control, 30 min flow control interval, perfect gate calibration

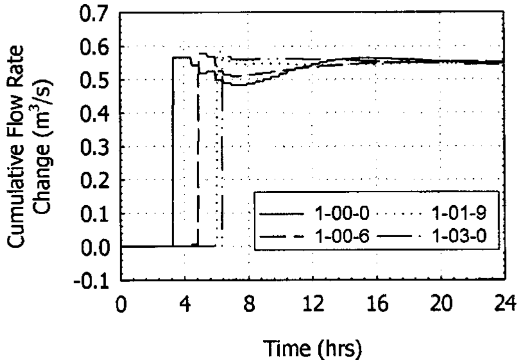

Fig. 7. Cumulative check flow changes for Scenario 1: feedback (PI^{+}_{-1}) and feedforward control, 30 min flow control interval, perfect gate calibration

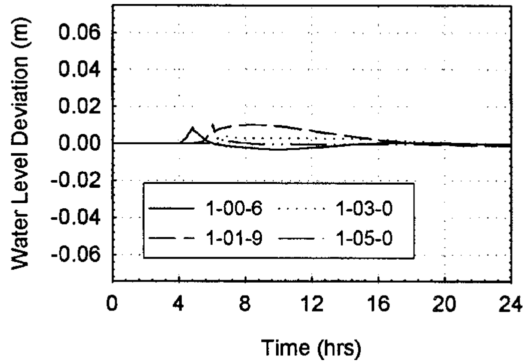

Fig. 8. Water level deviations for Scenario 1: feedback (PI^{+}_{-1}) and feedforward control, 30 min flow control interval, imperfect gate calibration

(Fig. 3). Note that the feedforward control actions are responsible for the largest deviations observed during the test. These deviations were strong enough to cause the feedback controller to request a flow cut (Fig. 7), thus slightly counteracting the feedforward action. For this example, this counteracting effect ultimately has little impact on overall performance, i.e., water level control with the combined system is still better than with either feedback or feedforward control alone. Still, this suggests potential performance improvements if feedback actions could take into account incoming feedforward actions.

The final simulation conducted with this scenario employed the combined control system and incorrect gate discharge relationships. Despite the apparently large differences between controller and simulator gate discharge predictions, water levels remained close to their targets throughout the test (Fig. 8). Water levels initially recovered more slowly than without gate calibration errors (Fig. 6), but peak deviations were similar as well as deviations at the end of the test.

Scenario 2

In contrast with the previous scenario, this example included multiple changes (Table 4) and an incorrect head-discharge relationship was used for one of the offtakes, in addition to the incorrect relationships for the check gates. With feedback control alone (using the PI^{+}_{-1} controller), absolute peak deviations were less than 4 cm (1.6 in.) and were close to 1 cm (0.4 in.) by the end of the test (Fig. 9). With combined feedforward and feedback control, absolute errors were less than 1 cm throughout the test and decreased with time, despite the error in offtake flow (Fig. 10). Similar results as those shown in Figs. 9 and 10 were obtained when using the PIL^{+}_{-} controller and, therefore, are not shown here. Clearly, this suggests that the combined control scheme can handle effectively multiple routine flow changes.

Scenario 3

As was explained earlier, this test represents an emergency situation in which the large demand change would be communicated to the operators late, precluding anticipatory control actions. For completeness, simulations were conducted first with feedback alone and with the combined system, assuming full precompensation of the change. Simulations were conducted later with two nonanticipatory, feedforward control strategies in combination with feedback control. As before, tests were conducted with both the PI^{+}_{-1} and PIL^{+}_{-} controllers but only PI^{+}_{-1} results are shown because performance differences were negligible. Gate errors were imposed on all of these simulations (Table 5).

With feedback alone, water levels deviations reached 0.6 m (2 ft), five times the maximum value that would be tolerated in practice (Fig. 11). Note also that the simulation was conducted for 48 h and that it took nearly 40 h to bring water levels close within the tolerance range. The controller response was stable, but there was some overshoot, that is, water levels first rose and then dropped below the target, as a result of controller-requested cuts that exceed the actual demand change. This suggests a controller that may be a bit too aggressive under the given conditions. Note that these results assume no constraints on the inflow delivered to the head of the canal. Such constraints might further reduce the ability to reject this disturbance.

Table 4. Scenario 2 Initial Check and Offtake Flows, Target Water Levels, and Demand Changes

Forebay and check ID	Initial check flows (m^3/s)	Forebay depth (m)	Major offtakes	Major offtake flows (m^3/s)	Demand change (m^3/s)	Time of change	Final check flow (m^3/s)
1-00-0	30.87						30.73
1-00-6	26.39	2.29	SRPMIC	4.25	−0.28	8:30 a.m.	26.54
1-01-9	26.28	1.77					26.42
1-03-0	26.22	1.83					26.37
1-05-0	14.81	1.83	2-00-0	11.33	−0.57	8:00 a.m.	15.52
			1-05-0	14.81	+0.71	9:00 a.m.	

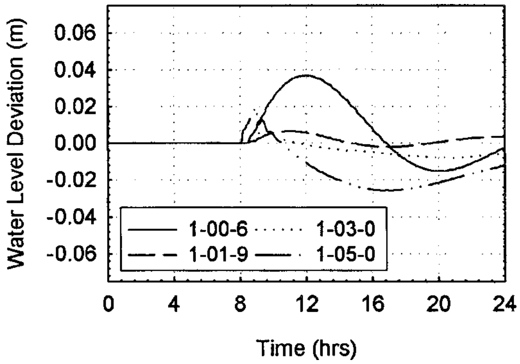

Fig. 9. Water level deviations for Scenario 2: feedback (PI_{-1}^{+}) control only, 30 min flow control interval, imperfect gate calibration

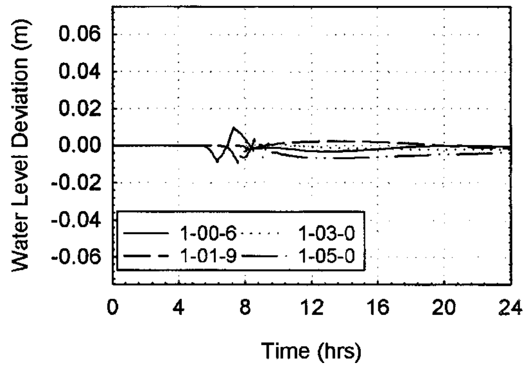

Fig. 10. Water level deviations for Scenario 2: feedback (PI_{-1}^{+}) and feedforward control, 30 min flow control interval, imperfect gate calibration

With feedforward control added (Fig. 12), water levels briefly moved out of the green range [less than 7.5 cm (0.25 ft)] but did not reach the red range [greater than 12 cm (0.4 ft)]. Noteworthy are the deviations in Pool 1-01-9. An initial and sharp water level fluctuation was followed by a slightly larger and longer fluctuation. The initial deviation was caused by the feedforward flow change. The second fluctuation resulted from pool imbalances induced by gate flow errors. Despite the gate calibration errors, the feedback controller performed effectively and was able to drive water levels within 3 cm of their targets by the end of the 24-h test.

With no prior knowledge of the demand change, the available open-loop control options are to cut back the inflow to all pools upstream from the pool with the demand change (and thus tolerate large level fluctuations within the canal), to pass the excess flow downstream, to spill excess flow through emergency drains, or some combination of all of the above. Simulations were conducted using the first option only. In such cases, watermasters would have to cut the discharge at all check structures by an amount equal to the emergency change and all of these changes would have to take place simultaneously. A simulation was conducted with this nonanticipatory, feedforward control strategy, in combination with feedback control (Fig. 13). Initial deviations increased rapidly and reached 30 cm in the upstream Forebay, 1-00-6. Water levels then decreased just as rapidly and eventually dropped more than 30 cm (1 ft) below the target. The initial rise in Forebay 1-00-6 is explained by the sudden reduction in pool outflows. The subsequent drop in water levels below the setpoint resulted from feedback control actions that counteracted the open-loop control action, as discussed for Test 1. Hence feedback caused water levels to fluctuate more than necessary. For better performance, such feedback actions need to be computed taking into account the open-loop control actions or vice versa.

An example of the open-loop control actions determined taking into account feedback effects is presented in Fig. 14. Knowing that the feedback controller requests an inflow cut in response to the initial water level deviations, open-loop control flow changes were determined as a fraction of the known offtake change. The flow changes applied to each check structure were determined by trial-and-error and are given in Fig. 14. Results show again some overshoot, but not as extreme as in Fig. 13 (although deviations lasted longer). Therefore control may improve with open- and closed-loop control strategies that better accounted for each other's effects (e.g., model predictive control). This issue requires further investigation.

Discussion

Overall, these results suggest the proposed control system is stable, robust, and will be able keep water levels within SRP's current tolerance range under typical operational conditions in the tested canal reach. As expected, better results were obtained when dealing with scheduled demand changes and with accurate gate calibration.

Results presented herein support previous analyses (Clemmens and Schuurmans 2004; Clemmens and Wahlin 2004) which suggest that there is little advantage in using the PIL_{-}^{+} feedback controller over the PI_{-1}^{+} controller. However, results cannot be generalized because the canals considered are relatively short and

Table 5. Scenario 3 Initial Check and Offtake Flows, Target Water Levels, and Demand Changes

Forebay and check ID	Initial check flows (m^3/s)	Forebay depth (m)	Major offtakes	Major offtake flows (m^3/s)	Demand change (m^3/s)	Time of change	Final check flow (m^3/s)
1-00-0	20.96						15.29
1-00-6	20.19	2.29	SRPMIC	0.54			14.53
1-01-9	20.08	1.77					14.42
1-03-0	20.02	1.83					14.36
1-05-0	12.91	1.83	2-00-0	6.94	−5.66	6:30 a.m.	12.91
			1-05-0	12.91			

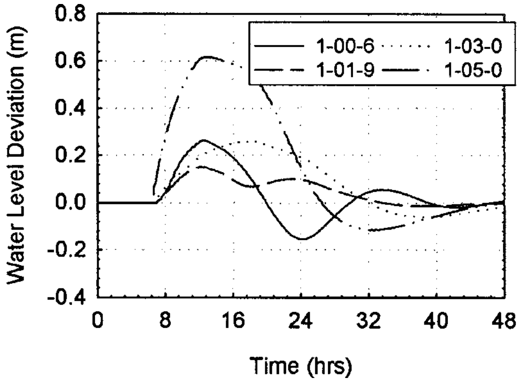

Fig. 11. Water level deviations for Scenario 3: feedback (PI^{+}_{-1}) control only, 30 min flow control interval, imperfect gate calibration

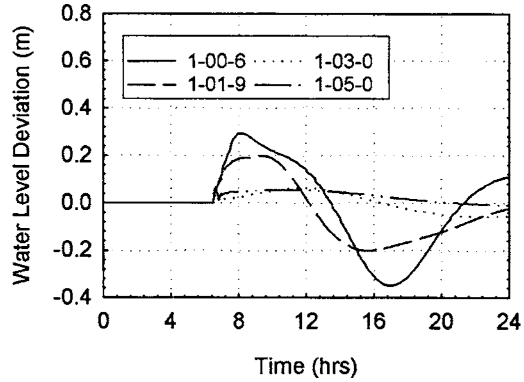

Fig. 13. Water level deviations for Scenario 3: feedback (PI^{+}_{-1}) and nonanticipatory feedforward control, 30 min flow control interval, imperfect gate calibration

the demand change conditions simple. Also, these results suggest feedback control alone can handle small routine changes effectively, but those results assume that there are no canal inflow restrictions. In reality, inflow cannot be varied freely because supply depends on very limited storage provided by a diversion dam at the head of the canal. Hence unscheduled changes cannot be supplied indefinitely unless compensated by changes in upstream reservoir outflow. Several approaches are currently being examined to deal with supply constraints.

The feedback controllers used here were tuned for discharge conditions similar to those of the tests. Therefore additional tests need to be conducted under both much higher and lower flow conditions. Alternatively, the feedback controllers can be tuned under very different flow conditions and tested with the examples presented above. Finally, the tests did not consider potential errors in the estimation of the canal's hydraulic resistance properties. Because the test reach is entirely lined, large changes in hydraulic resistance are not anticipated. Still, the effect of errors needs to be examined, as it affects both feedforward and feedback control performance.

The analysis considered errors of ±10% at check structures. As was indicated earlier, these errors are considered to be realistic under typical flow conditions for free-flowing check gates but errors at submerged gates may be potentially larger. Additional analyses are required prior to implementation to determine the potential range of discharge measurement errors at check structures and to determine if errors within that range could destabilize the feedback control system.

Conclusions

A control scheme was developed for the Upper Arizona Canal and tested with the *Mike 11* unsteady-flow simulation model. Control tests were developed based on scenarios provided by SRP watermasters. Small and large scheduled changes were handled satisfactorily with the combined feedforward-feedback control logic. Small unscheduled changes were handled effectively with feedback control alone. In all of these cases the control system was able to keep Upper Arizona Canal water levels mostly within the target band (i.e., within the "green" range tolerated by operators), even when gate hydraulic relationships assumed by the controller differed from those employed in the simulator. Nevertheless, results show that better knowledge of gate hydraulic relationships improves the control system's performance.

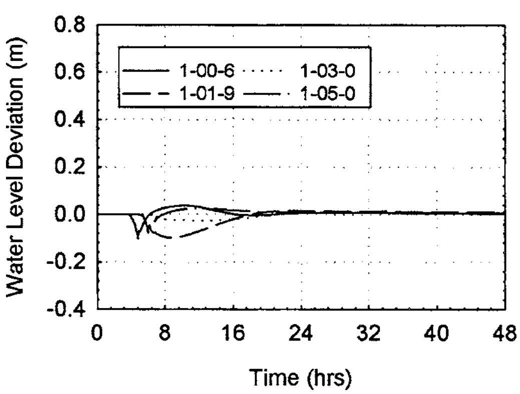

Fig. 12. Water level deviations for Scenario 3: feedback (PI^{+}_{-1}) and feedforward (anticipatory, feedforward) control, 30 min flow control interval, imperfect gate calibration

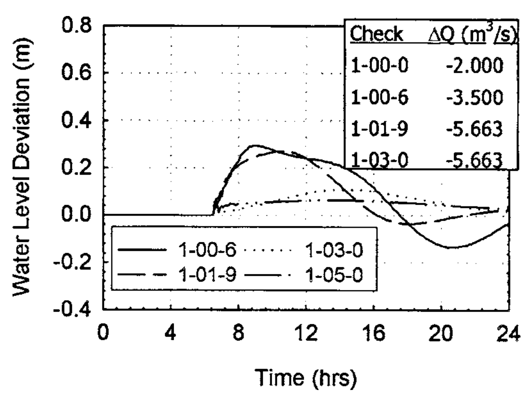

Fig. 14. Water level deviations for Scenario 3: feedback (PI^{+}_{-1}) and modified, nonanticipatory feedforward control, 30 min flow control interval, imperfect gate calibration

While results show that the feedback controller can reject small, unscheduled demand changes, in reality those results are subject to supply limitations dictated by the storage behind the diversion structure that feeds the canal. Assuming no supply limitations, the feedback controller alone was able to reject a large unscheduled demand change. However, the resulting water level deviations greatly exceeded operator-tolerated values.

Notation

The following symbols are used in this paper:

A, **B**, **C**, and **D**	=	feedback controller state-transition matrices;
e	=	water level deviation;
$\mathbf{e}$	=	feedback controller vector of outputs;
$\mathbf{K}$	=	gain matrix of feedback controller;
k,n	=	integers;
n	=	Manning roughness coefficient;
t	=	time;
$\mathbf{u}$	=	vector of control actions of feedback controller;
$\mathbf{x}$	=	vector of system states of feedback controller;
y	=	observed water level;
y_{stp}	=	pool downstream water level setpoint;
ΔQ	=	check flow rate change;
ΔQ_{fb}	=	feedback flow rate change;
ΔQ_{ff}	=	feedforward flow rate change;
Δq_{ot}	=	offtake flow rate change;
ΔT_{fb}	=	feedback control time interval;
ΔT_Q	=	flow control time interval;
ΔV	=	pool storage change;
Δw	=	check gate level change; and
$\Delta\tau$	=	wave travel time or delay.

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